

Prepared for 3rd Symposium
on Engineering Aspects of
Magnetohydrodynamics,
Univ. of Rochester, N. Y.,
March 28-29, 1962

FACILITY FORM 602

N65-86646

(ACCESSION NUMBER)

20
(PAGES)

(NASA CR OR TMX OR AD NUMBER)

(THRU)

(CODE)

(CATEGORY)

PRELIMINARY OBSERVATIONS OF R.F. POWER TRANSFER
TO A HYDROGEN PLASMA AT FREQUENCIES NEAR
THE ION CYCLOTRON FREQUENCY

By Clyde C. Swett and Roman Krawec

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

ABSTRACT

Apparatus and methods used to determine the amount of power transferred continuously to a hydrogen plasma at radio frequencies are described. A Philips-Ionization-Gauge type discharge was used as a source of initial ionization in a mirror-type magnetic field and a transmitter capable of supplying up to 15 kilowatts was used as the r.f. power source. The resistance which the plasma reflects back into the r.f. coil circuit was used to determine the amount of power transferred to the plasma. The light intensity of the plasma was measured and electron density was determined by means of microwave interferometer.

Although the investigation to date has been primarily concerned with initial phases of developing apparatus and procedures, some data have been obtained at powers up to 2 kilowatts. Power-transfer efficiencies of 50 to 60 percent were obtained at initial pressure levels of 0.5 to 2 microns. The measured electron densities were approximately 10^{11} electrons/cc, indicating about 1 percent ionization. The resonant point, identified as the point of maximum power transfer to the plasma, occurred at magnetic fields 18 to 47 percent greater than that corresponding to ion cyclotron resonance for atomic hydrogen ions. Light-intensity and electron-density measurements showed similar behavior. An explanation for this shift is presented.

INTRODUCTION

The production of a continuous source of highly-ionized hydrogen plasma has been undertaken as part of the plasma physics research program at NASA-Lewis Research Center. The method of plasma heating selected is the ion cyclotron resonance method in which r.f. power can be readily transferred to ions when the frequency of the power source is near the ion cyclotron frequency. As shown by Stix (Ref. 1) such transfer is possible at efficiencies of at least 85 percent, which is a marked improvement over that obtained using r.f. discharges without a magnetic field

E-1608

or with a magnetic field different than that required for ion cyclotron resonance. Since the degree of ionization is dependent on the power input, proper utilization of the resonance effect should be a valuable aid in the production of a highly-ionized plasma when the source of r.f. power is relatively limited.

Several experiments in which the ion cyclotron resonance method has been utilized have been reported (Refs. 1 to 5); however, these investigations have either been conducted using r.f. pulses of high power but short duration or else using continuous low-power (milliwatt level) signal generators. The present objective of using continuous but moderate amounts of power (15 kw) leads to different design and operating problems than previously encountered. For example, although Hooke et al. (Ref. 2) used a 1-megawatt r.f. pulse of about 4-millisecond duration, the actual energy transfer is less than would be put into the plasma by the 15-kilowatt source in 1 second; thus severe heating problems can be expected. Also, extra precautions are required to minimize electromagnetic radiation into radio communication bands. However, certain advantages are to be expected in a continuously operating system. Power measurement should be considerably easier to accomplish since time is available to properly match the r.f. source to the plasma under all conditions and power can be read directly from meters. Also, outgassing or cleanup of the vacuum system, which can be time consuming, should be swiftly accomplished by the continuous action of the plasma.

The research reported herein has been primarily concerned with initial phases of setting up the apparatus, developing the necessary procedures for operation and control, and analyzing the circuitry. Some preliminary data on power transfer to the plasma have nevertheless been obtained as a consequence of checking out the apparatus and procedures and these have been included. The data taking has been limited to power levels of 1 to 2 kilowatts. Higher power runs will be made at a later date.

APPARATUS

A longitudinal cross-section of the ion cyclotron resonance apparatus (ICRA-2) is shown in Fig. 1. Ultra-pure hydrogen flowing continuously at about 2 to 14 cubic centimeters per minute at atmospheric pressure and room temperature was introduced into the Philips-Ionization-Gauge (P.I.G)-type discharge and pumped out at the other end of the system by means of a 6-inch diffusion pump. The base pressure of the system was about 10^{-7} millimeter of mercury. The operating pressure was controlled by the amount of gas flow and was measured at the center of the apparatus by a McLeod gauge having a liquid-nitrogen cold trap. The 4-inch I.D. pyrex glass discharge tube had 3-inch I.D. arms in the center for the microwave horns, for connections to the shield, and for connection to the McLeod gauge. Twelve water-cooled d.c. coils connected in series and supplied with up to 4400 amperes from remotely-controlled generators produced a maximum field of 10,000 gauss in the region of the

r.f. coil and 20,000 gauss in the mirrors. The field variation was $\pm 1\frac{1}{4}$ percent in the uniform region as measured by a nuclear-magnetic-resonance-type gauss meter. Figures 2 and 3 show a little of the detail of the d.c. coils and how the apparatus may be separated at the center for removal of the glass tubes or r.f. coils. Most of the operation of the apparatus and the instrumentation was done remotely from a control room (Fig. 4).

The P.I.G. discharge was located in the field of the large magnet so that the magnet coil on the P.I.G. was not required for operation. It was necessary to locate the P.I.G. discharge farther from the apparatus than desired for best performance with the result that the plasma column in the discharge tube was compressed to about $1/2$ inch in diameter at maximum magnetic field. Such small diameter is not desirable as shown by theoretical considerations for coupling between the r.f. coil and the plasma column. A new and larger source is being fabricated.

The r.f. coil was a four-section coil with four turns per section fabricated using $3/8$ -inch copper tubing coated with either polyethylene insulation or a baked epoxy tape. The coils were reverse wound and connected in the manner used in Ref. 1 to give the instantaneous field directions shown in Fig. 1. The wavelength (distance between the center of the first coil and the center of the third coil) was 16 inches and the I.D. of the coil was $5\frac{3}{8}$ inches. The coil was cooled with warm water (115° F) to prevent water vapor in the room air from condensing and dripping down onto the matching network terminals.

For most of the data reported herein an aluminum shield was used to shield the plasma from the electrostatic field of the r.f. coil. This shield was intended originally as a quick fix on a problem which arose during the tests and so was not designed to be a low loss shield. The results using it were so reproducible and interpretable that it was left in for this part of the program. The shield itself was rolled from $1/16$ -inch sheet in two sections, each section having a longitudinal slot. It would have been preferable to locate the shield outside of the vacuum tube, but insufficient spacing and voltage breakdown considerations forced the shield to be placed inside. Each section was grounded by a strap run from the shield to a flange in the bottom arm of the glass tube (see Fig. 1).

A block diagram of the r.f. system is shown in Fig. 5. All elements were well shielded except the leads to the coil. Field-intensity measurements verified the adequacy of shielding. The transmitter output was designed for 600-ohm load so it was necessary to add a balun between the transmitter and the matching network. A directional coupler was used to measure both the power output and any reflected power due to mismatch. In normal operation the matching network was carefully adjusted so that the reflected power was always less than 10 watts. As an additional check

as to whether the r.f. circuit was maintained as a purely resistive load and as an aid in tuning the network, the phase angle between the voltage and current at the network input was measured.

The network used to transform the impedance of the coil system so that it appears to be a 50-ohm resistance is shown in Fig. 6(a). Points at which the voltage and current of the coil circuit are measured are also shown.

R.F. CIRCUIT ANALYSIS

Considerable time was spent making impedance and resistance measurements on the r.f. coil both directly and by analyzing the circuit from voltage and current measurements both with and without plasma. Most of the measurements have been obtained with the shield installed and numbers quoted are for this particular case. The results indicated that the coil (shown inside of the dashed lines in Fig. 6(b)) acted like a capacitor C_p in parallel with a series combination of inductance L and resistance R_s . Resistance $R_s = R_c + R_p$ where R_c is the coil resistance and R_p is resistance reflected into the coil because of plasma. The capacitor C_p included the distributed capacitance of the coil, the capacitance to the grounded shield inside the vacuum tube, and the capacitance to a grounded shield located at the inside diameter of the d.c. coils. Approximate component values at 6.5 mc were $L = 2.7 \mu h$, $C_p = 120 \mu f d$ and $R_c = 0.5 \Omega$. Values changed slightly for different coils and installations. The self-resonant frequency of this combination was measured to be about 9 mc.

The circuit shown (Fig. 6(b)) has an equivalent circuit (Fig. 6(c)) such that,

$$R'_s = R'_c + R'_p = \frac{R_c + R_p}{\omega^2 C_p^2 (R_c + R_p)^2 + (1 - \omega^2 L C_p)^2}$$

$$\omega L' = \frac{\omega L (1 - \omega^2 L C_p) - \omega C_p (R_c + R_p)^2}{\omega^2 C_p^2 (R_c + R_p)^2 + (1 - \omega^2 L C_p)^2}$$

For the present case where $\omega^2 C_p^2 (R_c + R_p)^2 \ll (1 - \omega^2 L C_p)^2$ and $\omega C_p (R_c + R_p)^2 \ll \omega L (1 - \omega^2 L C_p)$

$$R'_s \cong \frac{R_c + R_p}{(1 - \omega^2 L C_p)^2}$$

$$L' \cong \frac{L}{1 - \omega^2 L C_p}$$

If L and C_p remain constant, $R'_C + R'_p$ is proportional to $R_C + R_p$ and L' is proportional to L . These values of $R'_C + R'_p$ and L' are the quantities the matching network must convert to 50 ohms resistance load.

At the matched condition the reactance of the circuit must be zero and the resistance must be 50 ohms; these occur when,

$$\omega C = \frac{\omega L' - \frac{1}{\omega C_s}}{(R'_S)^2 + \left(\omega L' - \frac{1}{\omega C_s}\right)^2}$$

and,

$$50 = \frac{R'_S}{(\omega C)^2 \left[(R'_S)^2 + \left(\omega L' - \frac{1}{\omega C_s} - \frac{1}{\omega C}\right)^2 \right]}$$

With L_m defined such that

$$\omega L_m = \omega L' - \frac{1}{\omega C_s}$$

the two equations can be expressed in terms of R'_S

$$\omega C = \frac{1}{50} \sqrt{\frac{50 - R'_S}{R'_S}}$$

$$\omega L_m = \sqrt{50 R'_S - (R'_S)^2}$$

The effect of R'_S on C and L_m is sketched in Fig. 7. As the load resistance R'_S increases C decreases and L_m increases or decreases depending upon the portion of the curve being considered. For the present work the values of R'_S were small so that the values of L_m were on the rising portion of the curve. Hence, as R'_S increased, L_m increased and C_s increased. If L' should change, L_m would also change, however, for the present work L' was constant; this was determined from the fact that C_s changed only slightly and in the amount to account for a different value of L_m as required by a larger value of R'_S .

PLASMA POWER MEASUREMENTS

There are two ways of determining the power which is transferred to the plasma. The first method consists of determining an efficiency of power transfer from current and power measurements. The resistance $R'_S = W/I^2$ where W is the amount of power put into the network when plasma is present. Without plasma (i.e., without hydrogen flow) the power input is W_c and the resistance $R'_C = W_c/I^2$. Hence

$$R'_P = R'_S - R'_C = \frac{W - W_c}{I^2}$$

and the percentage efficiency of power transfer is

$$\frac{R'_P}{R'_C + R'_P} \times 100$$

or

$$\frac{W - W_c}{W} \times 100$$

The power measurements must be made using the same current.

The second method consists of determining the load resistances R'_S and R'_C from the capacitance readings of C and C_S with and without plasma and then calculating the efficiency by

$$\frac{R'_P}{R'_C + R'_P} \times 100$$

The resistances can be obtained from the theoretical curves which show how C and L_m vary with the load resistance. Hence, from capacitance readings on C and C_S values of R'_S can be determined. In practice, it has been found that C_S varies only a slight amount (less than 5 μmfd) so that for the present situation C is a better quantity to use. The capacitive reactance of C is very low and even slight inductance (say 50 $\text{m}\mu\text{h}$) in series with C can cause an appreciable change in the capacitive reactance. Therefore, calibration of C must be made at the operating frequency or determined in some other manner.

Both of these methods have been used with less than 10 percent variation in results. Currently, the first method is being used, chiefly because of the ease of putting the measured quantities into a recording system.

MICROWAVE AND LIGHT-INTENSITY MEASUREMENTS

Electron densities were measured using an 8-millimeter-microwave interferometer. A diagram of the system is shown in Fig. 8 and the theory of operation is discussed in Ref. 6. The power levels in the two arms were made equal, and the amplitude of the combined signal was recorded with a camera mounted on the oscilloscope. The phase angle between the two signals is given by the relation:

$$\cos \theta = \frac{(P/P_1) - 2}{2}$$

where

θ phase angle

P_1 power in the reference arm

P vector sum of powers in the two arms, that is, the total power out

The electron density n_e in particles per cm^3 is then given by

$$n_e \approx 2.07 \times 10^9 f(\Delta\theta/l)$$

where

f generator frequency in kmc

$\Delta\theta$ phase angle change in degrees

l path length through the plasma in cm

The plasma was assumed to be a slab 2 cm thick with constant electron density throughout. No attempt was made to correct the data for the fact that the plasma was cylindrical.

The intensity of the light emitted from the plasma was measured with a type 931-A photomultiplier tube and recorded on an x-y plotter.

RESULTS AND DISCUSSION

All of the data presented herein have been taken with constant r.f. current of 22 amperes, frequency of 6.5 megacycles, and the aluminum shield in place, although some data have been taken without the shield. The results without the shield indicated a circuit behavior entirely different from that with the shield. Whereas data were reproducible and entirely consistent with all measured quantities for the runs with the shield such was not the case without the shield. Analysis of the data

lead to the conclusion that the parallel capacitance across the coil system (i.e., C_p in Fig. 6) changed not only with the field but with the amount of power. The effect of not considering this possibility in the data reduction is an apparent, but erroneous, large power transfer. Further investigation is needed before the no-shield results can be understood.

A typical set of data which show how the reflected resistance, electron density, and light intensity vary with magnetic field both with and without the P.I.G. discharge are shown in Fig. 9. The marked increase in reflected resistance, electron density, and light intensity because of the ionization from the P.I.G. discharge and because of some resonant effect is apparent. Without the P.I.G. discharge only 12 to 23 percent of the power was transferred to the gas whereas with the discharge the efficiency was 21 to 55 percent as marked at various points on the curves.

The electron-density and light-intensity measurements are shown in (b) and (c). Curves have not been drawn through the electron-density data points because of lack of sufficient number of points to determine a good average value. It is apparent that the electron density and the light intensity increase in a manner similar to the reflected resistance. With electron densities of about 10^{11} particles/cc the degree of ionization was quite low, less than 1 percent.

Efficiency of power transfer was affected somewhat by pressure as shown in Fig. 10. The reflected resistance and, hence, the power transfer increased with pressure, the maximum efficiency of 60 percent being obtained at 2.0 microns pressure. A few other efficiencies have been noted at various points on the figure.

All of the measurements described above show a peak, or at least an increase for field strengths above the theoretical ion-cyclotron-resonance value of 4220 gauss. This is contrary to the theoretical and experimental work done by Stix (Refs. 1 to 3) where the peaks depart from the ion-cyclotron-resonance point only when the electron density is greater than 10^{12} , and is contrary to the findings of other workers (Refs. 4 and 5) which show a small shift to lower fields as the density increases.

A tentative explanation for the present apparent contradiction can be made if a mixture of atomic and molecular ions is assumed to exist in the plasma. Meyerand and Brown (Ref. 7) describe a P.I.G. discharge similar to the one used herein and one which was found to generate both of these ions in approximately equal concentrations. Buchsbaum (Ref. 8) shows that a mixture can change the resonance point and identifies the resonant frequencies for a plasma consisting of two ion species as the roots of the following equation:

$$\begin{aligned}
 & (\omega^2 - \omega_b^2)(\omega^2 - \omega_{b1}^2)(\omega^2 - \omega_{b2}^2) \\
 & - \omega_p^2 \left[\omega^2 - \omega_b(x_1\omega_{b1} + x_2\omega_{b2}) \right] \left[\omega^2 - \frac{x_2f_1 + x_1f_2}{x_1f_1 + x_2f_2} \omega_{b1}\omega_{b2} \right] = 0 \quad (1)
 \end{aligned}$$

where

ω the wave frequency

ω_b the electron cyclotron frequency

ω_{bi} the ion cyclotron frequency of species i

ω_p the plasma frequency

x_1, x_2 relative concentration of species 1 and 2

f_i m/M_i

m mass of electron

M_i mass of ion of species i

Assuming equal concentrations of species 1 and 2 and if we let

$$\frac{\omega}{\omega_b} \ll 1, \quad \frac{\omega_{b1}}{\omega_b} = \frac{1}{2000}, \quad \frac{\omega_{b2}}{\omega_b} = \frac{1}{4000}$$

then (1) reduces to:

$$\left[1 + \left(\frac{\omega_p}{\omega_b} \right)^2 \right] \Omega^4 - \left[1.25 + 1500 \left(\frac{\omega_p}{\omega_b} \right)^2 \right] \Omega^2 + 0.25 + 750 \left(\frac{\omega_p}{\omega_b} \right)^2 = 0 \quad (2)$$

where

$$\Omega \equiv \omega/\omega_{b1}$$

The experimental conditions were such that at resonance $\omega_p/\omega_b \approx 0.2$. Thus, from (2)

$$\Omega \approx 0.705, 7.65$$

Thus a resonance should be observed at $B \approx 5980$ gauss. This value agrees quite well with the 2.0-micron data (Fig. 10), but the other pressure data fall between this value and the atomic-ion-resonance point. However, it should be noted that a resonant peak anywhere between ω_{b1} and ω_{b2} can be predicted by a suitable choice of concentrations of the two species. The assumption of equal concentrations seems reasonable, although we have no means at present to test its validity.

A number of modifications can be made to the apparatus which should result in improved power transfer. The coil resistance can be reduced by using cold water instead of warm water for the coolant and by silver-plating the tubing and connections. Larger initial diameter of the P.I.G. discharge column should improve the coupling between coil and plasma. Different power supplies for the P.I.G. should also result in greater ion densities and improved loading.

Certain other important investigations need to be conducted. The idea of two different ion species needs to be confirmed experimentally. A simple mass spectrometer capable of being placed in the plasma is being designed to determine the relative concentration of the two species. Contamination may be present in the system because of the plasma existing in the vacuum system for long periods of time and requires spectrographic examination. A mass spectrometer is being installed in the system to extend the research into this area. Also, an optical spectrometer is being installed for obtaining estimates of the ion temperature. Additional work with the photomultiplier used in conjunction with filters for observation of light of certain wavelengths will also be a valuable asset in analyzing the plasma.

SUMMARY AND CONCLUSIONS

The work described in this report may be summarized as follows:

1. Apparatus and methods have been developed to determine the amount of r.f. power transferred continuously to a hydrogen plasma. Reflected-resistance, light-output, and electron-density measurements have been made at constant r.f. current of 22 amperes (which resulted in powers up to 2 kw), constant frequency of 6.5 megacycles, pressures from 0.5 to 2.0 microns, and electron densities of about 10^{11} electrons per cubic centimeter.
2. Results show that the resistance reflected into the circuit increased with pressure and power transfer efficiencies as high as 50 to 60 percent were noted without resorting to special techniques.
3. There was a resonance identified as the point of maximum power transfer to the plasma which occurred at magnetic fields about 18 to 47 percent greater than that corresponding to ion cyclotron resonance for atomic hydrogen ions. Light-intensity and electron-density measurements showed similar behavior.

4. A possible explanation for this shift in the resonant point is that a mixture of atomic and molecular ions will show a resonant point different from that of either ion.

5. Further experimental evidence is needed to verify the concept of two ion species being present in the plasma.

REFERENCES

1. T. H. Stix and R. W. Palladino: Ion Cyclotron Resonance. Second United Nations International Conference on the Peaceful Uses of Atomic Energy, vol. 31, pp. 282-287.
2. W. M. Hooke, F. H. Tenney, M. H. Brennan, H. M. Hill, Jr., and T. H. Stix: Experiments on Ion Cyclotron Waves. Phys. Fluids, vol. 4, no. 9, Sept. 1961, pp. 1131-1141.
3. T. H. Stix and R. W. Palladino: Experiments on Ion Cyclotron Resonance. Phys. Fluids, vol. 1, no. 5, Sept. 1958, pp. 446-451.
4. L. V. Dubovoi, O. M. Shvets, and S. S. Ovchinnikov: Ion Cyclotron Resonance in Dense Plasmas. Plasma Physics (Journal of Nuclear Energy, Part c), vol. 3, 1961, pp. 203-208.
5. K. D. Sinel'nikov, V. T. Tolok, N. I. Nazarov, I. I. Bakaev, V. A. Bondarev, and Yu. P. Bugai: The Investigation of Ion Cyclotron Resonance in Dense Plasma. Soviet Physics Technical Physics, vol. 5, no. 3, Sept. 1960, pp. 261-265.
6. P. W. Kuhns: Microwave Interferometer Measurements of Electron-Ion Recombination in Nitrogen, Air, and Argon. NASA TN D-1191, Feb. 1962.
7. R. G. Meyerand and S. C. Brown: High-Current Ion Source. Rev. Sci. Inst., vol. 30, no. 2, Feb. 1959, pp. 110-111.
8. S. J. Buchsbaum: Resonance in a Plasma with Two Ion Species. Phys. Fluids, vol. 3, no. 3, May 1960, pp. 1-3.

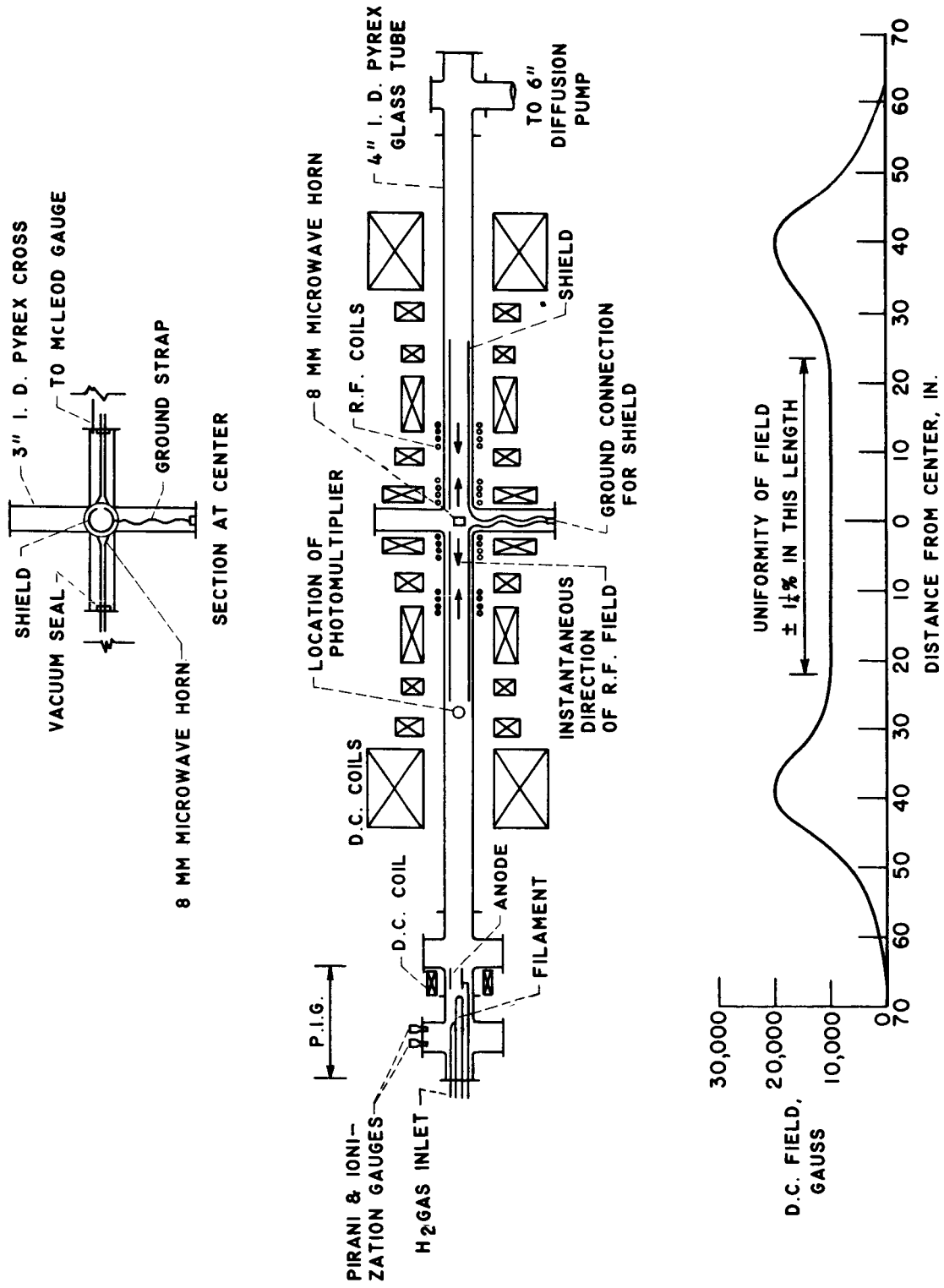


Figure 1. - Configuration of ion cyclotron resonance apparatus #2. (ICRA #2)

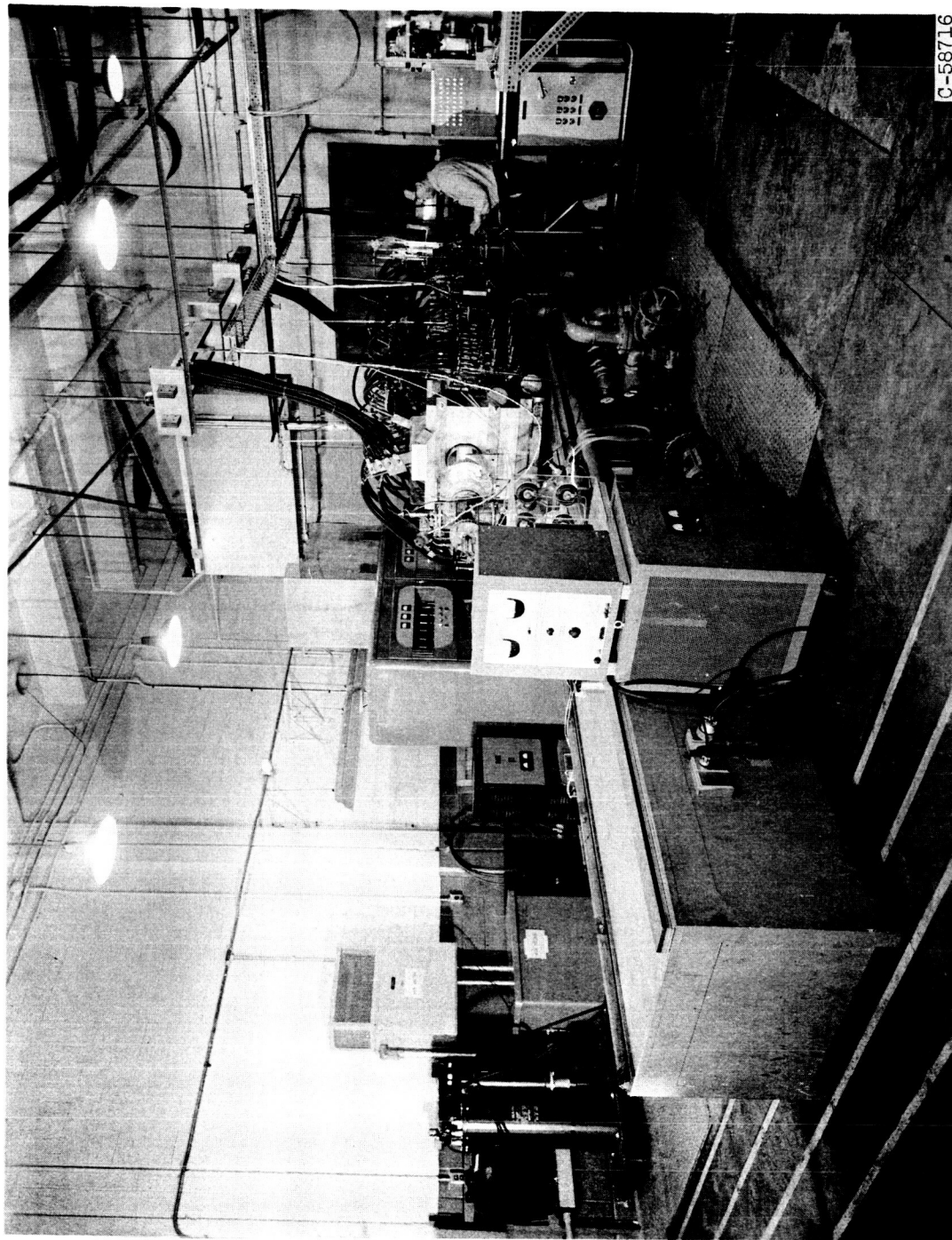


Figure 2. - Photograph of ion cyclotron resonance apparatus.

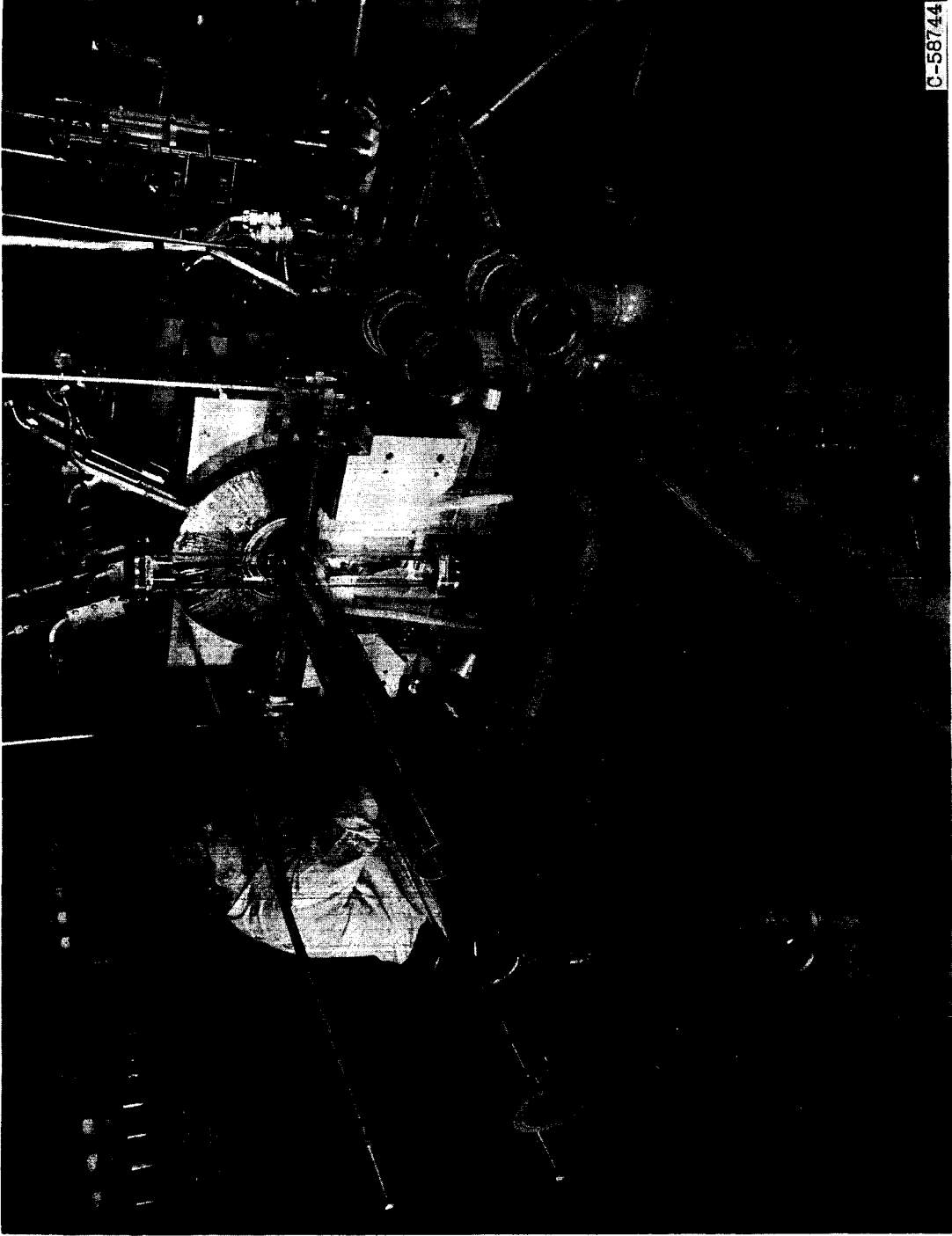


Figure 3. - View at center of apparatus with one-half of D.C. coil removed.



C-58715

Figure 4. - Control room.

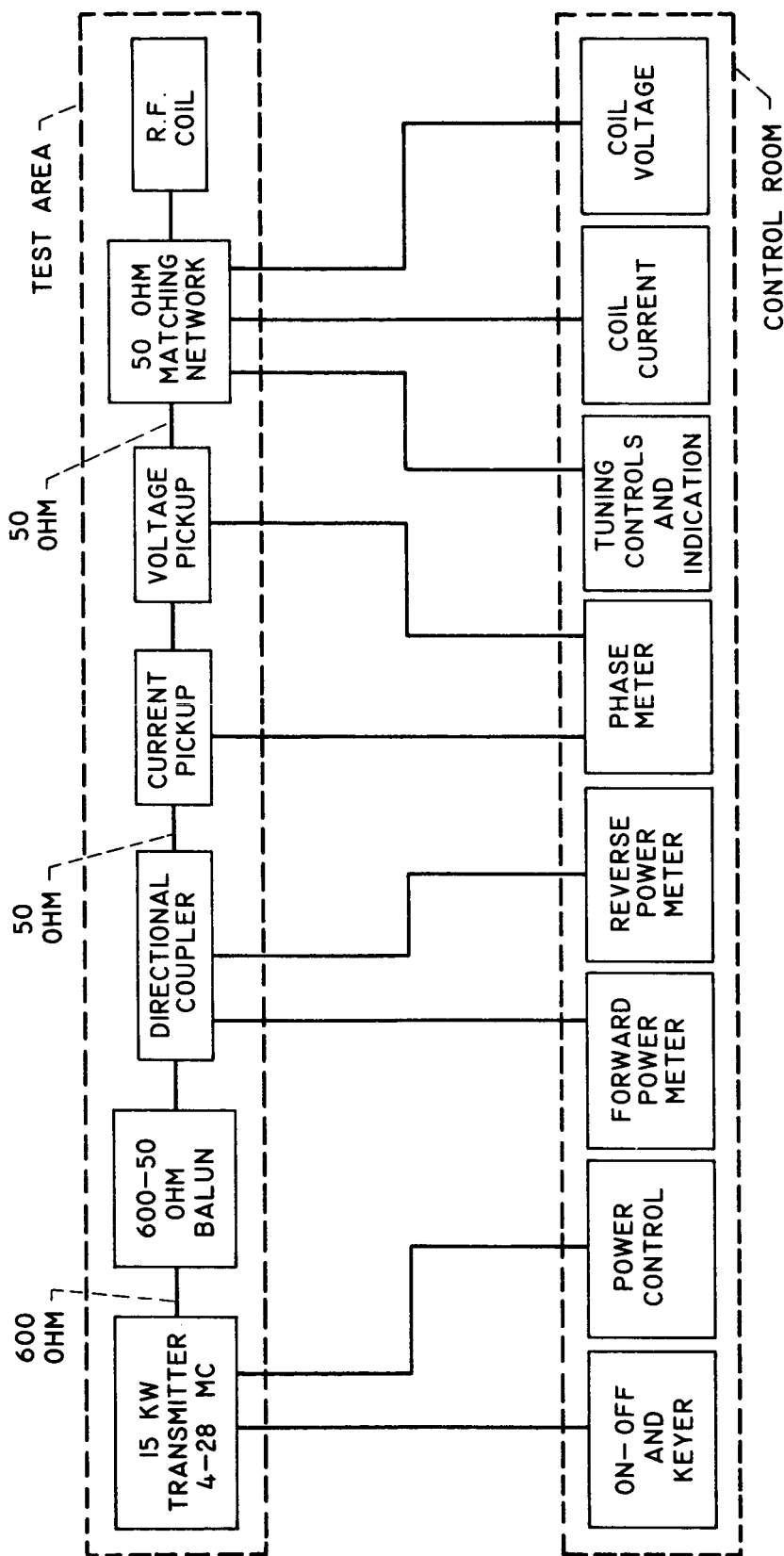
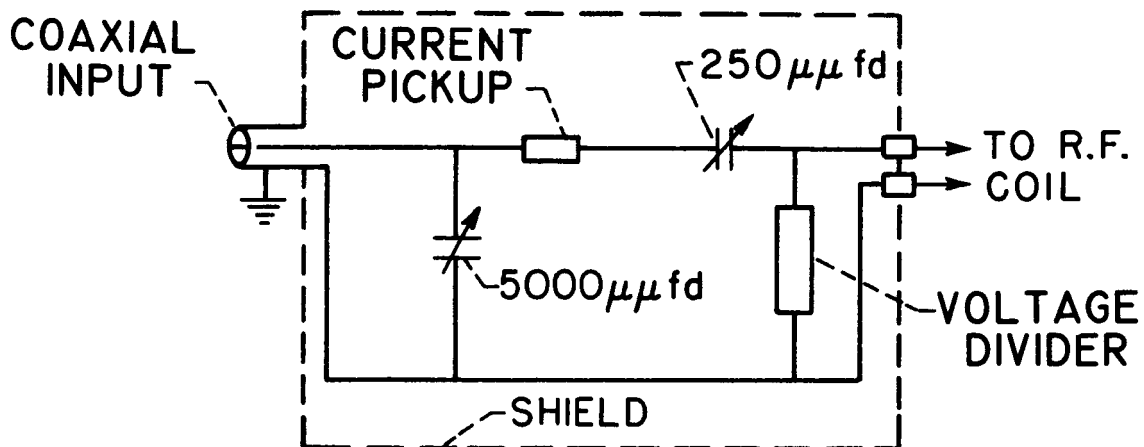
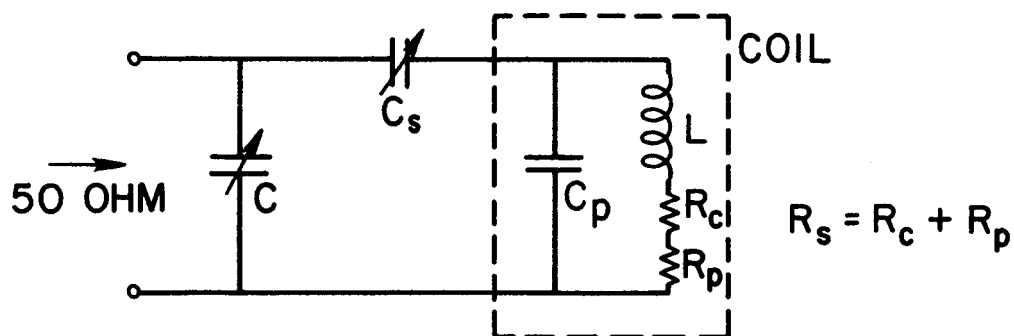


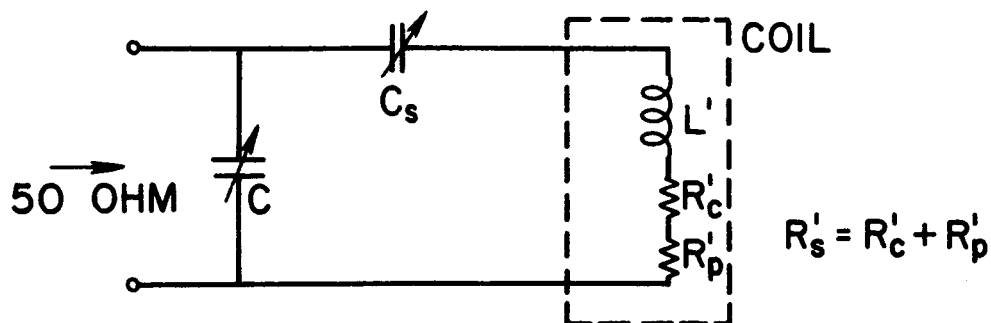
Figure 5. - Block diagram of R.F. circuit.



(a) Actual circuit.



(b) Basic circuit.



(c) Equivalent circuit.

Figure 6. - Actual, basic and equivalent R.F. circuit.

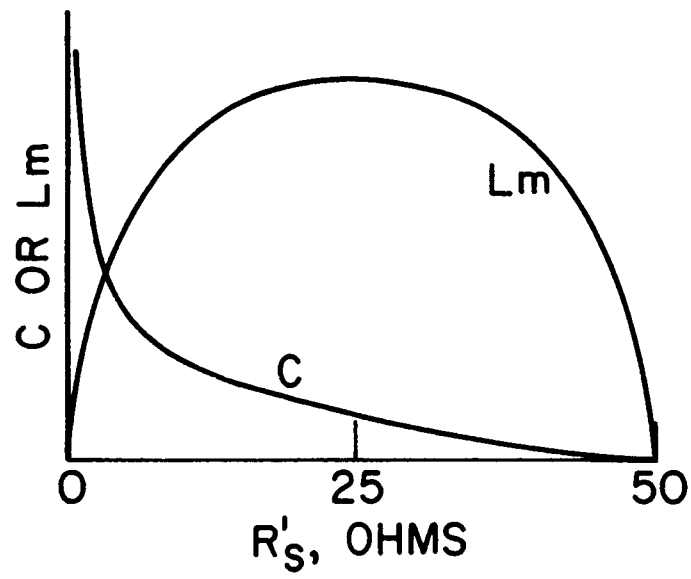


Figure 7. - Effect of load resistance R'_S on C and Lm .

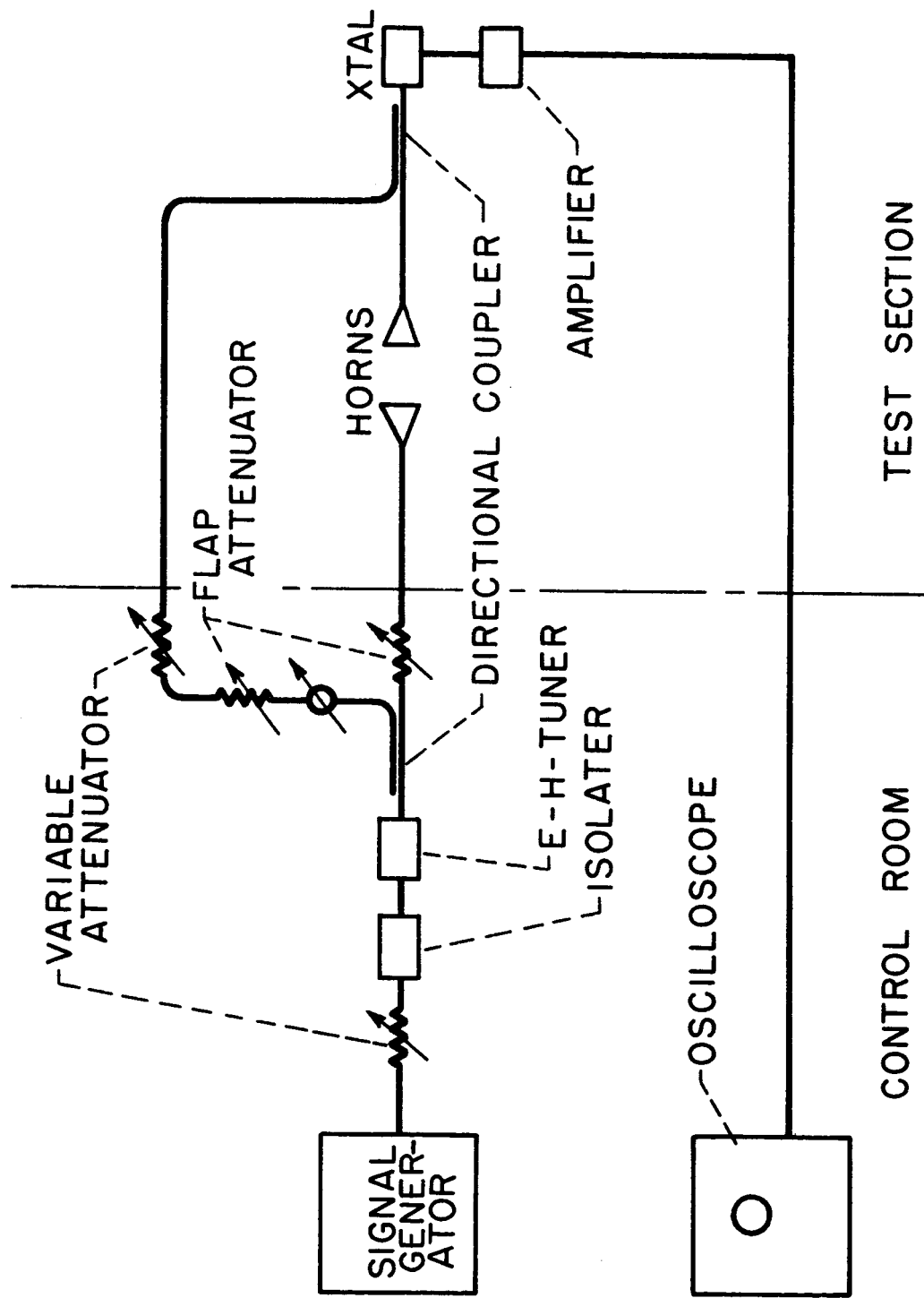


Figure 8. - Microwave interferometer.

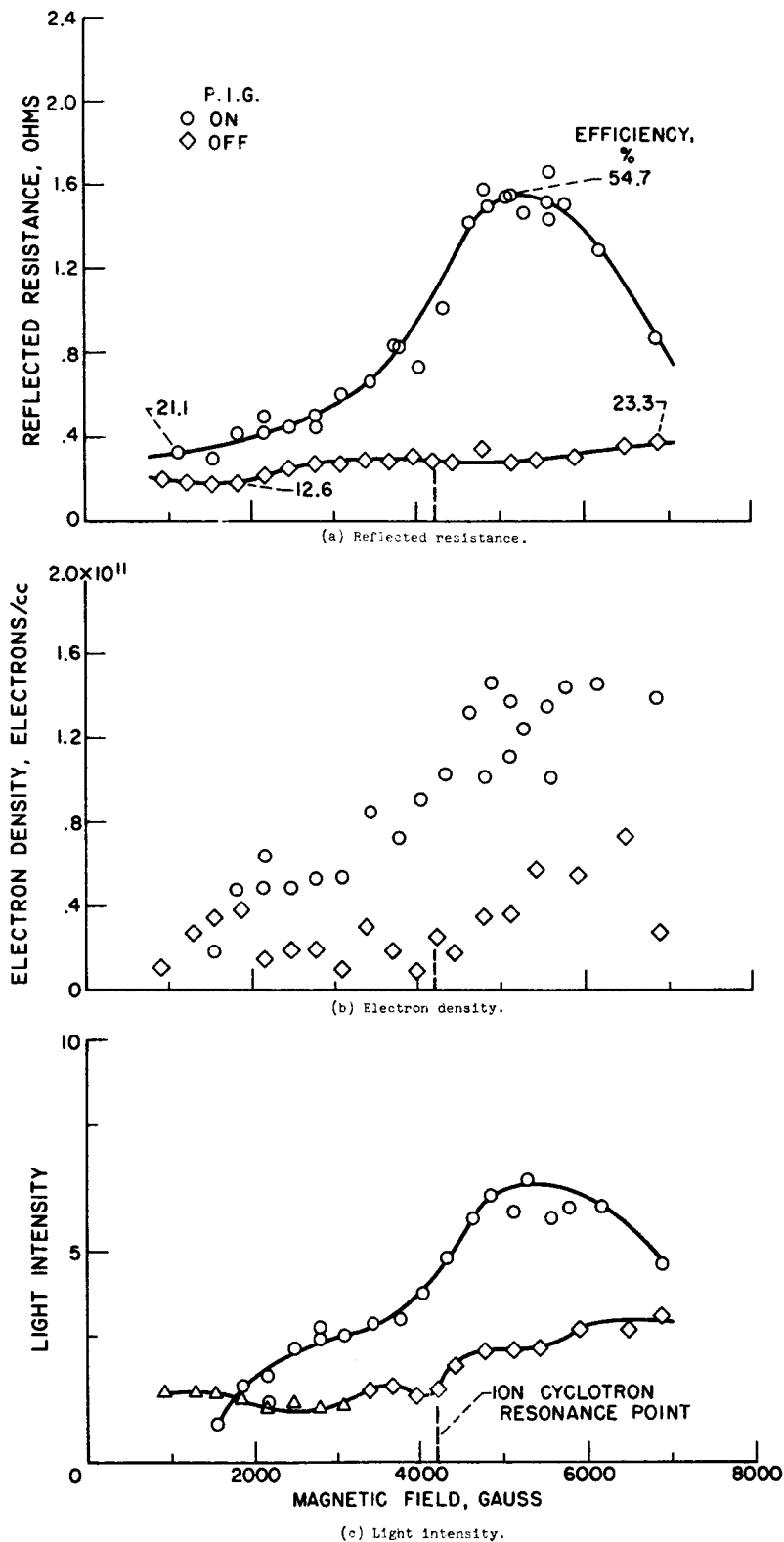


Figure 9. - Reflected-resistance, light-intensity, and electron-density data with and without P.I.G. discharge. Pressure, 1.0 micron; frequency, 6.5 megacycles; r.f. current, 22 amperes.

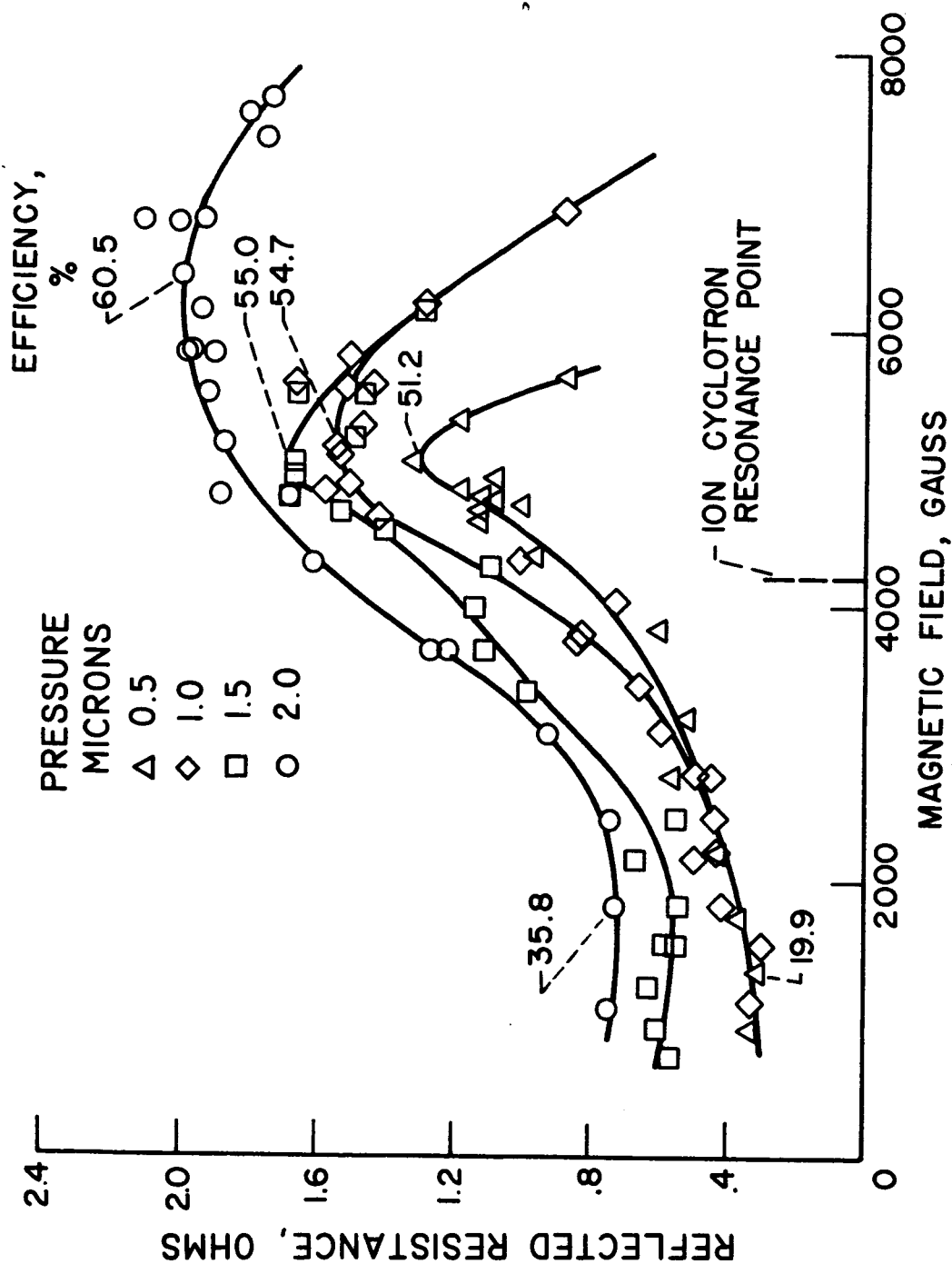


Figure 10. - Resistance reflected into circuit due to plasma. P.I.G. discharge on; frequency, 6.5 megacycles; r.f. current, 22 amperes.